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AEROELASTIC STUDY OF WIND TURBINE BLADE

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ABSTRACT: In the upper latitudes, wind turbines provide an effective means to generate wind power. However, owing to the fact that wind speeds are almost half in the tropical regions, wind turbines are yet to make significant penetration in tropical countries. Even 500 kW turbines tend to be large and slender. Such structures are known to be quite flexible. It is often not necessary to stiffen them excessively owing to weight penalty which also results in other problems like increased tower thrust and higher cut in speed. In the present paper, we present results of aeroelastic studies of low speed 500 kW wind turbine being developed by the National Aerospace Laboratories custom designed for tropical regions. The airloads are estimated using in-house developed Panel Method (inviscid) and the structural deformations are computed using ANSYS. The results indicate that the power output is affected by flexibility. Depending on the wind speed, the power generated actually may increase.

1. INTRODUCTION

Extraction of wind energy by use of wind turbines has proven to be an attractive augmentation for energy requirements. Wind turbines of varying capacity have been in use at upper latitudes for some decades now [1,2,5]. In fact, single machines of 2 Mega Watt capacity are currently in use. On the other hand, it is difficult to extract large amount of energy in the tropics [6]. This is owing to the fact that the wind speeds are much lower in the tropics compared to the speeds prevalent in upper latitudes. In fact, the speeds in the tropics are nearly half in comparison to the winds at upper latitudes. In spite of this limitation, India still has fairly large wind potential. Owing to the fact that the wind power varies as cube of wind speed, one cannot hope to extract same amount of energy from an imported turbine which is often designed around higher wind speed. Therefore, it is imperative that turbines must be designed for site specific applications for maximum extraction of power.

In the National Aerospace Laboratories, Bangalore, 500 kW machine is currently being designed. The design makes use of custom designed aerofoils [3,4]. The diameter of this turbine turns out to be 45 meters. A similar sized turbine could extract much more energy in the upper latitudes. The blades are designed using composite materials and tend to be very slender and flexible. This can result in prove to be a fairly complex aeroelastic problem.

In this paper we present a study focusing on the aeroelastic aspects of the wind turbine blade which makes use of in an in-house developed Panel Method for estimation of aerodynamic loads and ANSYS for structural response. Though flow separation cannot be accounted for, this study shows that the blade flexibility can have some effect on the power extracted. The blade frequencies are also somewhat altered by the flexibility. The analysis is useful as a starting point for more elaborate CFD based studies.

2. PROBLEM FORMULATION

Aeroelastic analysis involves two steps: computation of airloads and an assessment of structural deformation under these loads. Since structural deformation in turn affects airloads which are function of geometry, the final deformed shape and airloads cannot be determined in one step. These problems are well studied in aerospace sector in areas such as wing flutter. Different approaches exist. Often, airloads are computed using very simple methods like lifting line theory [8]. The primary reason for this is that the airload calculations often take an order of magnitude more computing power than calculation of structural deformation. Sometimes, it is also not necessary to compute the airload distribution very accurately. With the availability of enormous computing power, though, it is now feasible to use Panel methods, Euler solvers and even Navier-Stokes solvers for airload computations. However, the question of coupling them still remains. There are very few capabilities which provide a unified framework for full coupling.

In the present case, we adopt the following procedure. The aerodynamic model is divided into a number of quadrilateral panels. Each of the four corners of these panels is taken to the nodes for FEM analysis using ANSYS. Undeformed basic model is analysed using Panel Method to obtain surface pressures and associated forces. These forces are used to calculate the nodal forces on the FEM model. Since surface forces are computed on control points, usually geometric centroid, on the panels, the nodal forces are interpolated by equally distributing surface forces onto the nodes. We denote these by F1. Note again that FEM discretization coincides with the Panel method discretization. The nodal forces are used in ANSYS to compute the deformation using static analysis. This forms the zeroth iteration. The displacements obtained from the static analysis are added to the basic coordinates describing the blade geometry to generate the new deformed configuration. This configuration is further analysed using Panel method to obtain new surface pressure forces. These forces are again transformed, i.e., interpolated, to the nodes as before. These forces are denoted by F2. The crucial step is now to recognize that the new model is stress free and has already undergone deformation due to F1. Therefore, the difference of the forces, viz., $F2-F1$, is applied to the deformed model in ANSYS. This results in further deformation to give new displacements. These are added to the preceding coordinates to get the new deformed model. The procedure is repeated until convergence. Convergence is obtained when additional deformation is negligible. Typically only four iterations are needed for most cases for convergence.

The Panel method solves essentially Laplace equation for velocity potential. The effect of lift is accounted for by means of a distribution of line vortices. The strength of these vortices is determined simultaneously by satisfying zero normal velocity at each control point on panels and a Kutta condition at the blade trailing edge. [8, 9].

The ANSYS program has many finite-element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis. The 500 kW wind turbine blade finite element (FE) model is built in ANSYS by writing and executing a set of macros. The structural analysis of this model is carried out in two parts; first linear static analysis is performed to determine the displacements that define the deflected shape and second the modal analysis is performed to get the natural frequencies and corresponding mode shapes using Block Lanczos option.

3. RESULTS AND DISCUSSION

The wind turbine blade was analysed for wind speeds of 5, 10, 12, 15, 20 and 25 m/s. The wind speed of 12 m/s corresponds to the design wind speed. This wind speed was chosen by the design team based on site specific measurements which showed this to be the most frequently occurring speed. For brevity, we present results for wind speeds of 12 m/s wherein the power increases with flexure and 5 m/s in which case the power decreases slightly.

3.1 Wind turbine blade structural model

The structural model for 500 kW wind turbine blade was created in ANSYS using glass fabric laminates (foam sandwich construction). A combination of two glass fabrics with fiber orientation of $\pm 45^\circ$ and 0° was used. Two shear webs were placed at 10% and 50% chordwise locations inside the blade that ran from root to tip of the blade. A typical 13 layer lay-up was used for skin and shear webs. Construction and material details[7] are as follows:

Lay up: +45/-45/0₄/foam/0₄/+45/-45.

Material-1:

Glass fiber/epoxy (45-bi-directional material)

$E_x=41.4$ GPa, $E_y=E_z=6.9$ GPa and $\gamma_{xy}=0.15$, $G_{xy}=3.45$ GPa, $G_{yz}=G_{xz}=2.3$ GPa, $\rho=1940$ kg/m³

Material-2:

Uni-directional glass fiber/epoxy

$E_x=34.167$ GPa, $E_y=E_z=5.9627$ GPa and $\gamma_{xy}=0.15$, $G_{xy}=4.1417$ GPa, $G_{yz}=G_{xz}=2.7611$ GPa,

$\rho=1940$ kg/m³.

Material-3:

Foam

$$E_x=E_y=E_z=50 \text{ MPa and } \gamma_{xy}=0.25, G_{xy}=G_{yz}=G_{xz}=20 \text{ MPa, } \rho=148\text{kg/m}^3.$$

The weight of the wind turbine blade is 2241kg. This matched the actual blade within 2 per cent. Here E is Young's modulus and G is shear modulus. Quantity γ is Poisson's ratio and ρ is density.

Case 1: Analysis for wind speed of 12 metres per second

Fig. 1 shows the final converged shape and the wind turbine blade. Convergence is obtained at the third iteration. The "undeformed" shape for the third iteration is the deformed shape at the end of second iteration. The final tip displacement is about 0.01 m. Figs. 2, 3 and 4 show the distribution of out of plane moments. There is a clear concentration of M11 towards the leading edge on the suction side. Fig. 4 shows minor concentration of M12 near the hub region.

Figs. 5 and 6 show the transverse shear force. These distributions are quite normal over most of the turbine blade.

Figs. 7, 8, 9 and 10 depict the mode shapes of the final converged model. The first mode shape is mostly bending while the second one is mostly torsional in nature. The third mode is also mostly bending with one node (second bending mode) and the fourth mode is torsional with one node (second torsional mode). These are consistent and as expected.

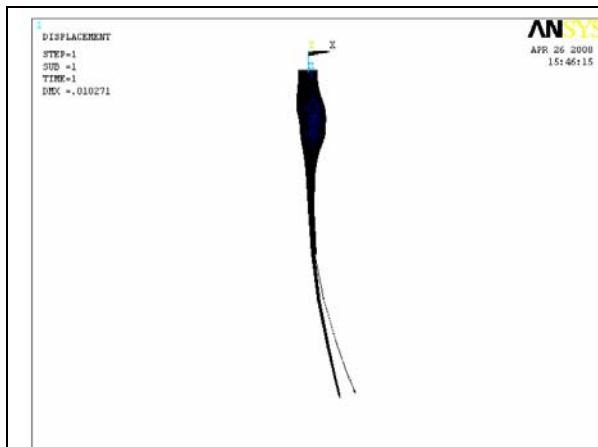


Fig.1 Deformed and undeformed shape of the model for the third iteration (Converged).

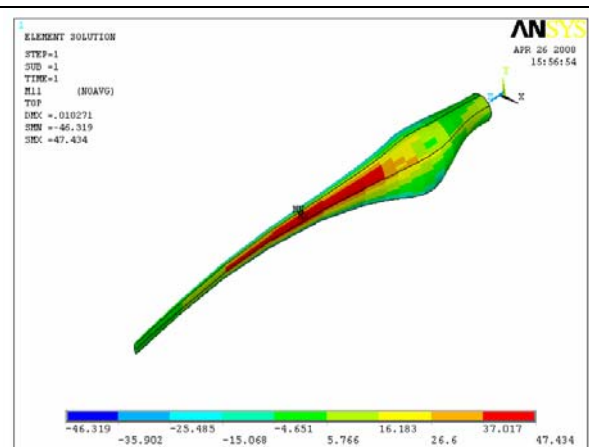


Fig.2 Out of plane moment M11

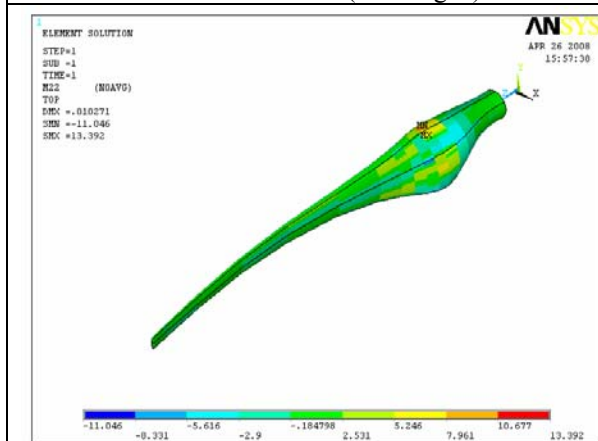


Fig.3 Out of plane moment M22

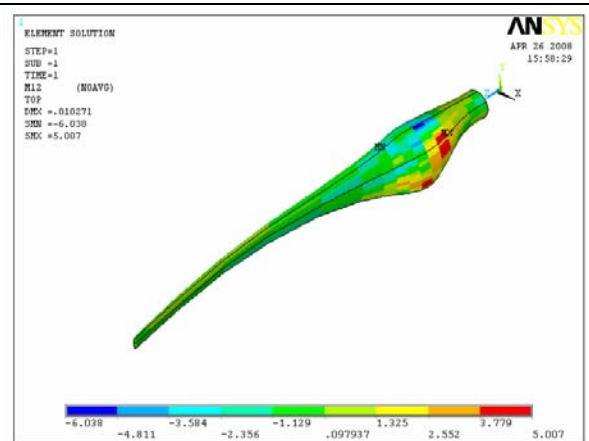


Fig.4 Out of plane moment M12

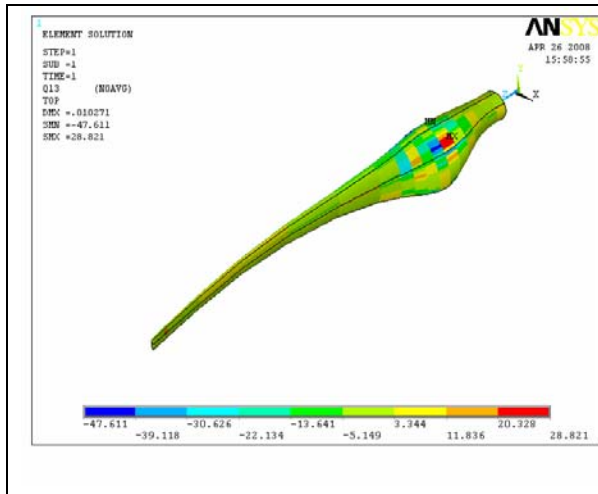


Fig.5 Transverse shear force Q13

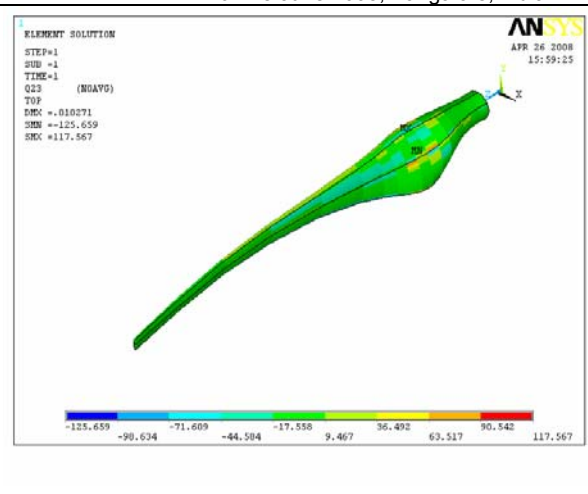


Fig.6 Transverse shear force Q23

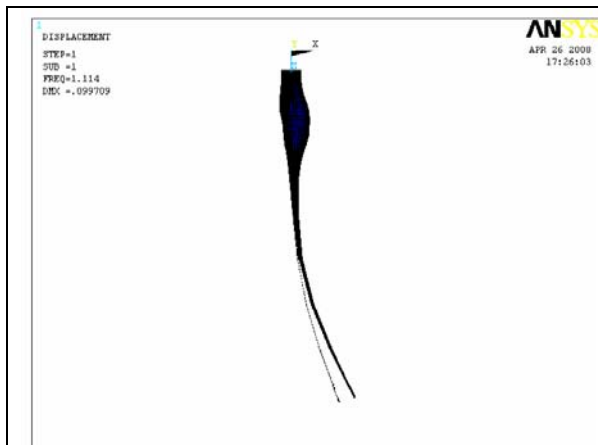


Fig.7 First mode shape of the converged model

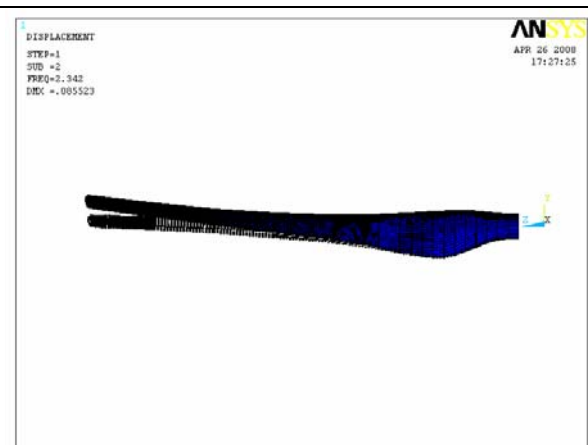


Fig.8 Second mode shape of the converged model

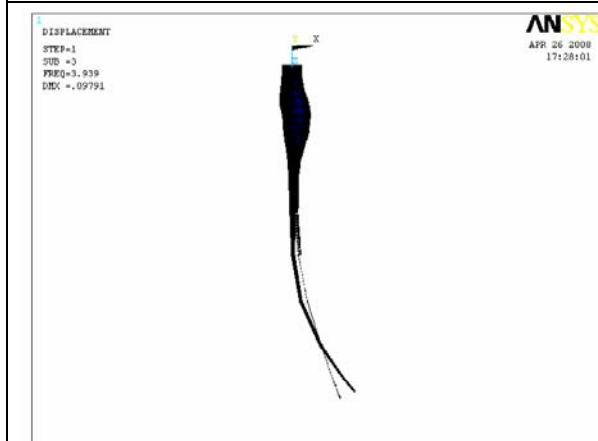


Fig.9 Third mode shape of the converged model

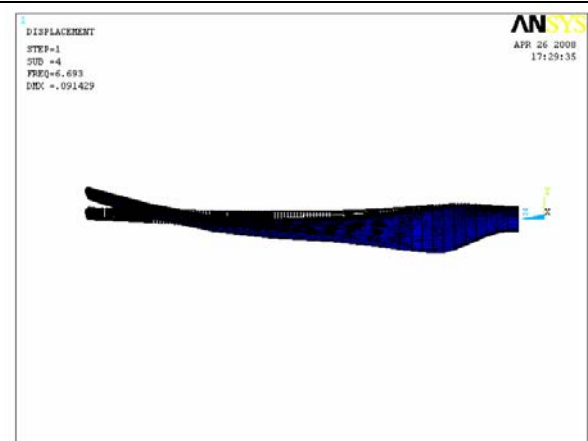


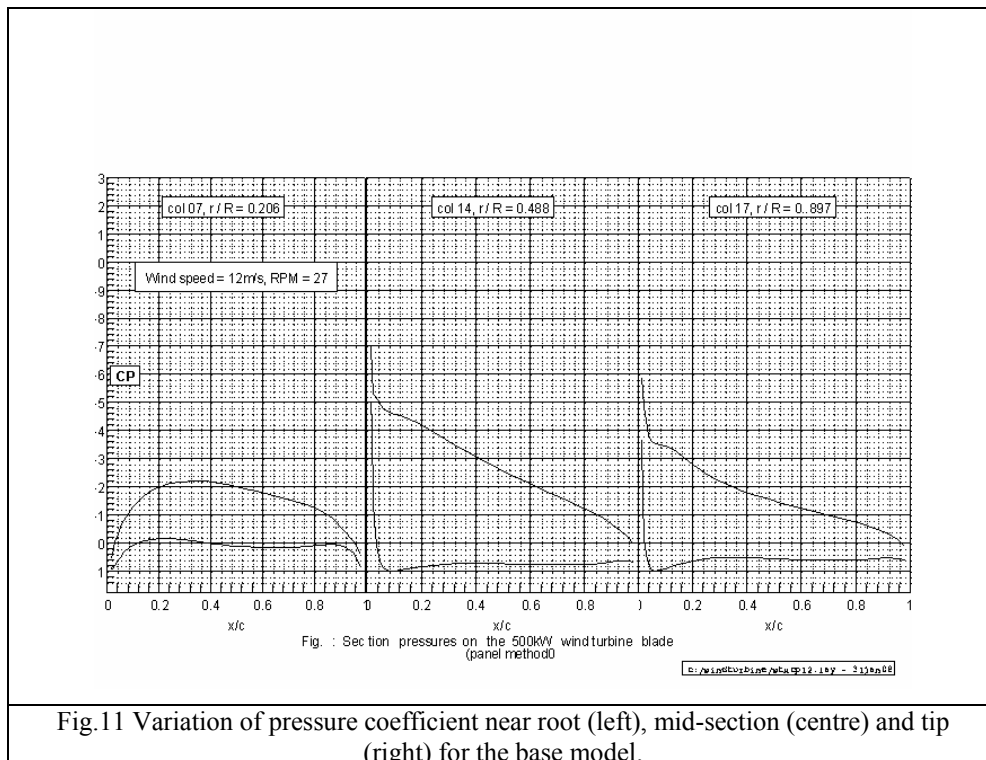
Fig.10 Fourth mode shape of the converged model

The frequencies are summarized in Table 1. The results clearly indicate that the frequencies decrease with the deflection. The thrust and power are summarized in Table 2. Both the thrust and the power increase.

Table 1: Modal frequencies (Hz)		
Mode number	Base model (iteration 0)	Converged model (iteration 3)
1	1.1605	1.1138
2	2.6740	2.3416
3	4.1100	3.9392
4	8.5342	6.6930

Table 2: Thrust and Power for wind speed of 12 m/s and RPM=27		
	Thrust (kN)	Power (kW)
Iteration 0	83.99	798.97
Iteration 1	86.46	813.49
Iteration 2	86.23	810.56
Iteration 3	86.24	810.65

The chordwise distribution of pressure coefficients are depicted in Figs. 11 (for base model) and 12 (converged model) at three typical sections (root, mid and tip). While the nature of distribution is different for each section, the variation is not very pronounced when the blade is deflected. The integrated effect, however, is seen in the thrust and power.



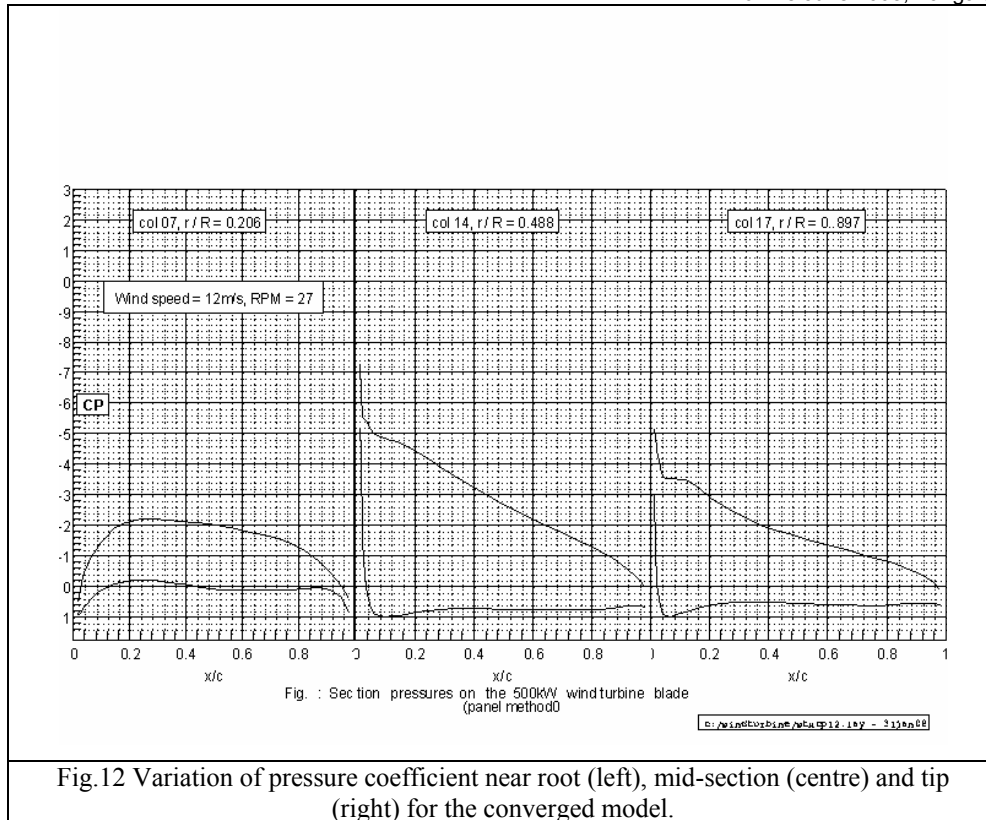


Fig.12 Variation of pressure coefficient near root (left), mid-section (centre) and tip (right) for the converged model.

Case 2: Wind speed of 5 metres per second

Fig. 13 shows the final converged shape and the wind turbine blade. Convergence is obtained at the third iteration. The “undeformed” shape for the third iteration is the deformed shape at the end of second iteration. The final tip displacement is about 0.07m. Figs. 14 shows the distribution of out of plane moments. There is a clear concentration of M11 near the hub region.

Figs. 15 and 16 show the transverse shear force. These distributions are quite normal over most of the turbine blade.

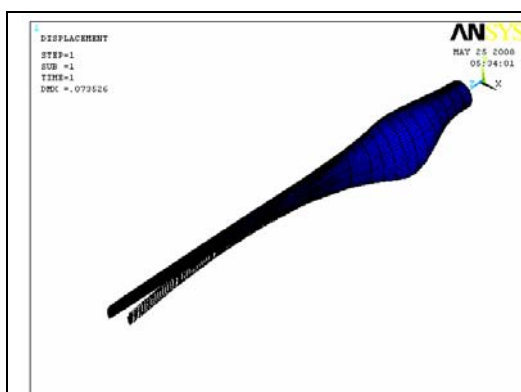


Fig.13 Deformed and undeformed shape of the converged model

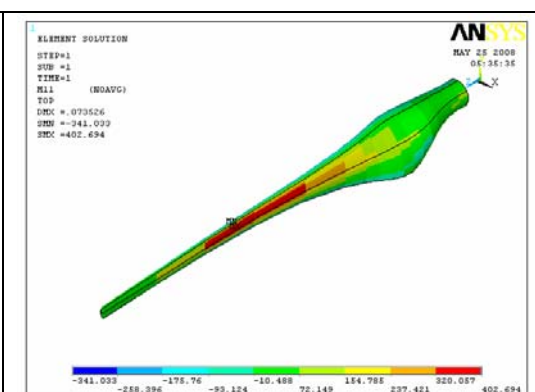


Fig.14 Out of plane moment M12

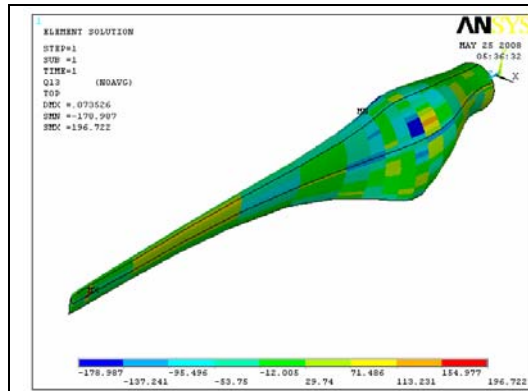


Fig.15 Transverse shear force Q13

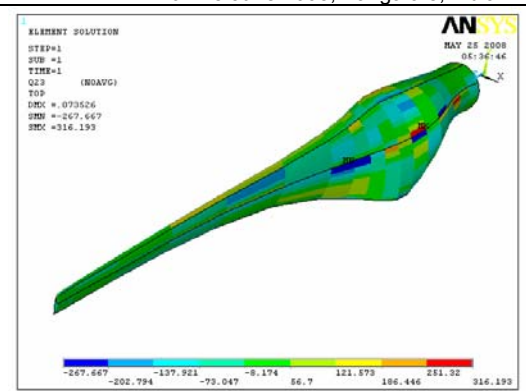


Fig.16 Transverse shear force Q23

The frequencies are summarized in Table 3. The results clearly indicate that the frequencies decrease with the deflection. The thrust and power are summarized in Table 4. The thrust is increasing and the power is decreasing.

Table 3: Modal frequencies (Hz)

Mode number	Base model (iteration 0)	Converged model (iteration 3)
1	1.1605	1.1412
2	2.6740	2.5106
3	4.1100	4.0317
4	8.5342	7.9486

**Table 4: Thrust and Power for wind speed
of 5 m/s and RPM=27**

	Thrust (kN)	Power (kW)
Iteration 0	42.47	93.04
Iteration 1	44.21	81.22
Iteration 2	43.25	85.25
Iteration 3	43.24	85.48

The chord wise distribution of pressure coefficients are depicted in Figs. 17 (for base model) and 18 (converged model) at three typical sections (root, mid and tip). While the nature of distribution is different for each section, the variation is not very pronounced when the blade is deflected. The integrated effect, however, is seen in the thrust and power. This is consistent with the earlier case of 12 m/s. The pressure distributions, however, differ for the present case, especially near the root compared to 12 m/s.

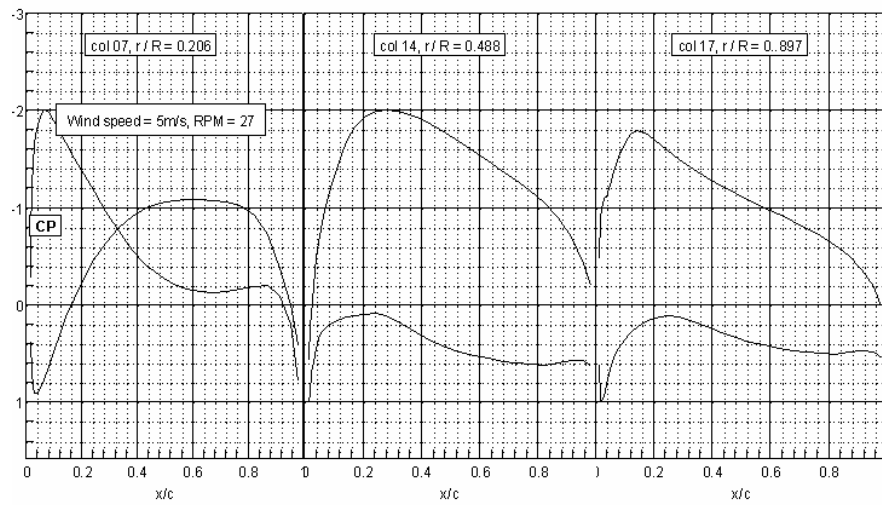


Fig. : Section pressures on the 500kW wind turbine blade
(panel method)

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Fig. 17 Variation of pressure coefficient near root (left), mid-section (centre) and tip (right) for the base model.

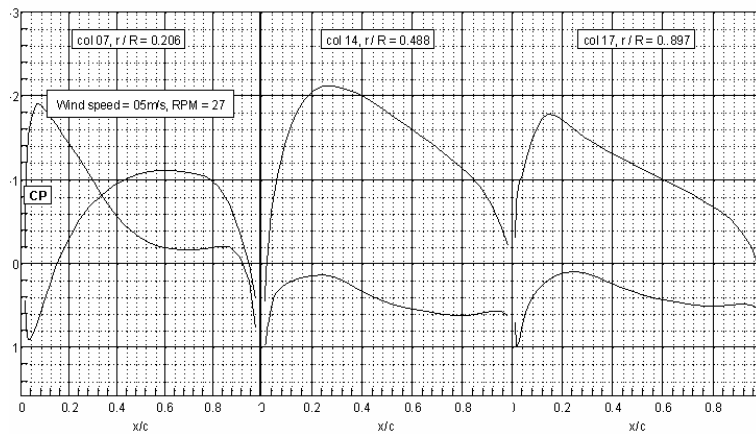


Fig. : Section pressures on the 500kW wind turbine blade
(panel method)

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Fig. 18 Variation of pressure coefficient near root (left), mid-section (centre) and tip (right) for the converged model.

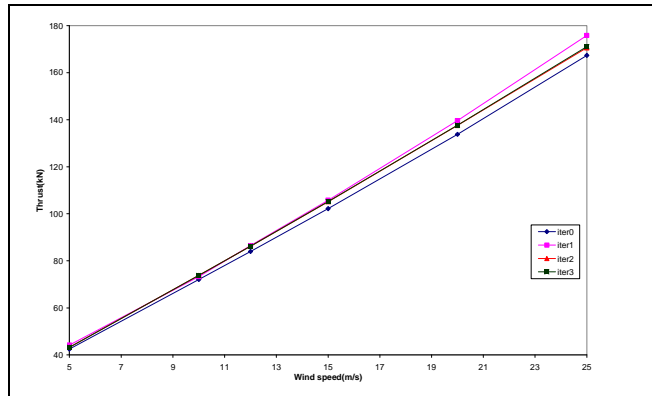


Fig.19 Variation of thrust with wind speed

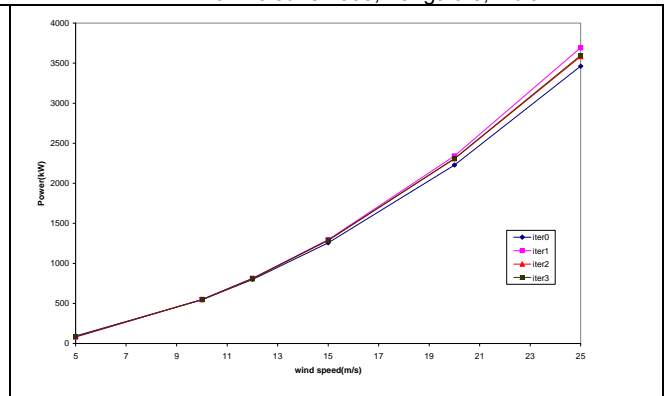


Fig.20 Variation of power with wind speed

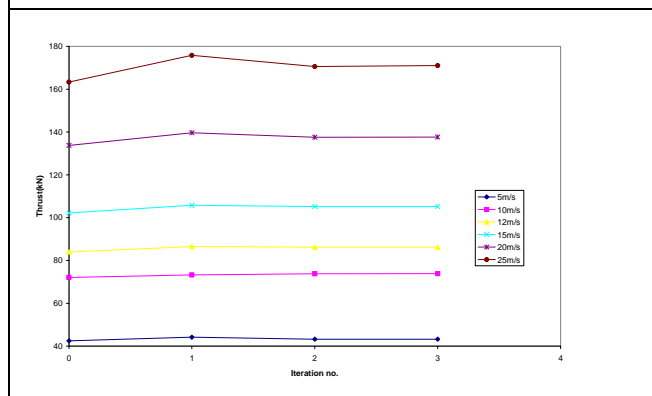


Fig.21 Variation of thrust with no. of iterations

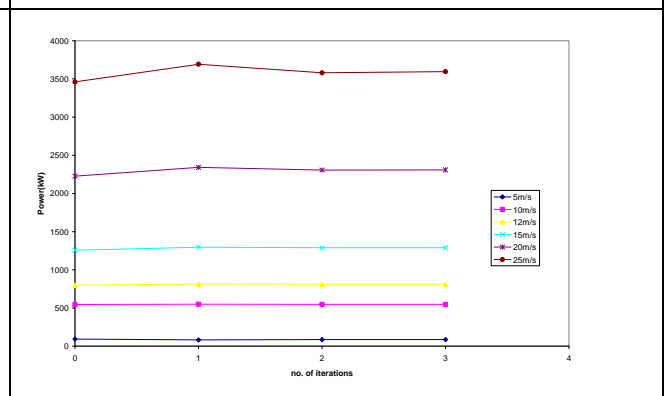


Fig.22 Variation of power with no. of iterations

4. CONCLUDING REMARKS

Composite low speed 500 kW wind turbine blade has been analyzed for aero elastic effects. The air loads are computed using a simple Panel method and the structural deformations are computed using ANSYS. Coupling procedure adopted has been specified. The results indicate that at lower wind speeds, the flexibility results in a slight decrease of power and beyond 10 m/s the effect is to increase the power. In fact, for 20 m/s and above, the power extracted due to flexibility is considerably higher.

Keeping the limitations of use of Panel method in the context of stall regulated wind turbine, it is imperative that one must make a more careful analysis using full CFD to account for flow separation. It is of interest to know whether the flow separation is affected by blade flexibility. This is left as future exercise.

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